ANALYSIS AND ESTIMATION OF THE GEOSAT SEA STATE BIAS

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1. INTRODUCTION

1.1 GOAL OF THE STUDY

The study presented here has been performed by CLS for HUGHES STX CORPORATION under subcontract agreement n°96-3056-K1196.

The goal of the study is to identify and calibrate the best possible model for the GEOSAT altimeter sea state bias (SSB). This study is based on the new JGM3 Geophysical Data Records recently prepared by NOAA (Cheney, 1996)

1.2 PRINCIPLE FOR SEA STATE BIAS ESTIMATION

The SSB determination method used here was developed by Gaspar et al. (1994) to estimate and operationally monitor the SSB of the TOPEX and POSEIDON altimeters. An outline of the method is provided below. For a detailed description, the reader is referred to Gaspar et al. (1994).

The altimeter-derived Sea Surface Height (SSH) relative to the reference ellipsoid can be decomposed as :

$$SSH = SSH' - SSB. \tag{1}$$

where SSH' simply is the SSH measurement before SSB correction. The goal of this work is to find a modeled sea state bias (SSB_m) that minimizes the variance of ΔSSH, the crossover differences. The candidate SSB models are chosen from a hierarchy of simple linear models linking SSB to the significant wave height (SWH) and wind speed (U). The general formulation of these models is :

$$SSB_m = SWH\,[a_1 + a_2\,SWH + a_3\,U + a_4\,SWH^2 + a_5\,U^2 + a_6\,SWH\,U] \tag{2}$$

The models being linear, parameter estimation reduces to a simple, generally multivariate, linear regression problem. The regression reads :

$$\Delta SSH' = a_0 + \Delta SSB_m + \varepsilon \tag{3}$$

where Δ denotes measurement differencing at a crossover point, ε is the regression residual and a_0 is a dummy coefficient formally needed as the mean of $\Delta SSH'$ might not be exactly zero. Series of regressions are performed with models based on (2) starting with the simplest 1-parameter model (BM1) :

$$SSB_m = a_1 \, SWH \tag{4}$$

and progressively increasing the number of adjustable parameters. The model finally selected is the model :

a) with the smallest possible number of adjustable parameters,
b) with regression residuals that are as little correlated as possible with the regressors (SWH and U).

2. DATA SET

2.1 DATA CONTENT

Based on the new JGM3 GEOSAT GDRs, NOAA prepared and provided a complete crossover data set (Lillibridge, 1996; personal communication). This data set covers :

- the whole Gravity Mission (GM) from March 31, 1985 to October 4, 1986;
- cycles 1 to 44 of the Exact Repeat Mission (ERM) from November 8, 1986 to November 27, 1988).

The crossover differences are computed over individual cycles (17 days) for the ERM and over periods of 23 days, corresponding to an orbital pseudo-cycle, for the GM. The data set includes 24 such pseudo-cycles.

The new JGM3 GDRs feature several important improvements compared to the T2-GDRs of Cheney et al. (1991), the most important ones being the JGM-3 orbit (Williamson and Nerem, 1994) and the CSR 3.0 ocean tide model (Eanes, 1994). The other changes are described in the JGM3 GDR handbook (Cheney, 1996). For the wet and dry tropospheric corrections, two fields can be chosen from the the GDRs :

- Wet : TOVS/SSMI correction (already featured in the T2-GDRs) or the correction deduced from the recent NMC reanalysis (Kalnay et al., 1996)
- Dry : correction deduced from the ECMWF model analysis (already featured in the T2-GDRs) or from the NMC model reanalyis.

For the wet tropospheric correction, we chose the NMC solution as it provides a slightly smaller variance of the crossover differences and, more importantly, uninterrupted data series. For the dry tropospheric corrections, the 2 proposed corrections are virtually identical in terms of variance of the crossover differences. We decided to use the NMC values so that the wet and dry tropospheric corrections consistently come from the same meteorological analysis. The inverse barometer correction is then deduced from the NMC dry tropospheric correction.

The wind speed is deduced from the backscatter coefficient (σ_0) using the Freilich and Challenor (1994) Rayleigh-based relation. Numerical inversion of this function provides the 19.5-m neutral stability wind speed as a function of σ_0. This wind speed is then divided by 1.057 to obtain the 10-m neutral stability wind speed (U) (e.g. Witter and Chelton, 1991a).

2.2 DATA EDITING

Before performing SSB analysis, anomalous or unreliable crossover data were eliminated. This is the case for all measurements

- with missing standard corrections
- with crossover differences larger than 0.5 m (in absolute value)
- with SWH> 11 m
- with U<1.5 m/s or U>20 m/s

Also, GEOSAT mispointing is known to adversely affect altimeter performance. Estimation of SWH and σ_0, is specially sensitive to this problem. As recommended by Cheney et al. (1991), measurements with ξ >1.1° are considered unreliable and are discarded.

After data editing, the number of validated crossovers is close to 1,096,000. This includes 647,000 crossovers from the GM and 449,000 from the ERM. The mean number of data per (pseudo-)cycle is thus about 27,000 for the GM and slightly over 10,000 for the ERM.

The standard deviation of the crossover differences (before SSB correction) is 14.1 cm for the GM, 14.3 cm for the ERM and 14.2 cm for the global (GM+ERM) data set, a truly remarkable result when compared to the 30 to 40 cm rms differences obtained with the T2-GDRs.

3. PRELIMINARY DATA ANALYSIS

The presence of the SSB is easily detected in uncorrected crossover differences (ΔSSH') when these are binned as a function of ΔSWH or ΔU. For example, if the SSB was simply a constant fraction of SWH, as modeled by BM1, the difference ΔSSH' would contain a term a_1 ΔSWH appearing as a linear trend when ΔSSH' is plotted as a function of ΔSWH. Such a linear trend is detected in figure 1a, but only for small values of ΔSWH ($|\Delta SWH| < 2$m). Deviations from linearity appear at larger values of ΔSWH. The SSB is also known to vary with wind speed. Accordingly, coherent changes of ΔSSH' as a function of ΔU are observed (figure 1b).

More surprisingly, figure 1c reveals variations of ΔSSH' as a function of $\Delta\xi$, indicating that the range measurements still contain an uncorrected attitude effect. This effect causes mean range differences of 2 to 3 cm when $\Delta\xi$ exceeds 0.5°. This unexpected behavior is investigated in the next section.

4. THE RESIDUAL ATTITUDE BIAS

4.1 A MODEL FOR THE RESIDUAL ATTITUDE BIAS

The impact of mispointing on altimeter range measurements is well known. Brown (1977) showed that off-nadir pointing (of typically a few tenths of a degree) induces a range measurement error proportional to the square of the attitude angle, the proportionality factor being a function of SWH. Based on numerical simulations of the POSEIDON altimeter performance , Raizonville (1986) showed that this error, hereafter referred to as the attitude bias (ATB), is well approximated by

$$\mathrm{ATB} = (b + c\ \mathrm{SWH})\ \xi^2 \tag{5}$$

where b and c are constant coefficients. Although GEOSAT range measurements are corrected for an attitude bias, figure 1c indicates that the applied correction does not totally eliminate the attitude-related error. It is likely that the residual error (δATB) still is, dominantly, of the form (5). If this is the case, the SWH-related component of this error (SWH ξ^2) will inevitably perturb our SSB estimation based on regressions with models like (2). The term purely proportional to ξ^2 is less of a problem as the (empirical) correlation between ξ^2 and SWH or U is very weak (the order of 0.01). Fortunately, it appears that the residual attitude bias observed in the GEOSAT data is well represented by the simple model :

$$\delta\mathrm{ATB} = b\ [\xi^2 - \langle\xi^2\rangle] \tag{6}$$

where $\langle\xi^2\rangle$is the average value of ξ^2 (in this case, 0.45 degree^2). This constant term is (arbitrarily) added to δATB to make sure that the average correction is zero and therefore does not change the measured mean sea level. The model parameter b is determined to minimize the variance of the corrected crossover differences, i.e. it is deduced from the simple regression :

$$\Delta\mathrm{SSH'} = b_o + b\ \Delta\xi^2 + \varepsilon \tag{7}$$

where b_o is a dummy coefficient. This regression, performed with the global (GM + ERM) crossover data set, yields b = 0.03 m/degree^2, where b is the estimated value of b. The explained variance is 1.63 cm^2.

Figure 2 shows the residuals of regression (7) plotted as a function of $\Delta\xi$. They are now negligibly small thereby indicating that the simple correction (6) has eliminated nearly all of the remaining attitude bias. Residuals of this same regression plotted as a function of ΔSWH and ΔU are virtually indistinguishable from those plotted in figure 1, thereby confirming that the modeled δATB is not significantly correlated with SWH and U.

4.2 ANALYSIS OF THE BIAS

To evaluate the uncertainty on $\hat{b}$, we performed series of regression (7) with individual repeat cycles or pseudo-cycles. The estimates of b for each (pseudo-)cycle are plotted in figure 3. Notice that the results for the ERM cycles are plotted first (cycles 1 to 44). The 24 GM pseudo-cycles are (arbitrarily) numbered 45 to 68. Figure 3 reveals two surprising features :

1) Estimates of b are more scattered during the GM than during the ERM : their standard deviation is 0.02 m/degree^2 for the GM and only 0.01 m/degree^2 for the ERM.
2) The estimate of b deduced form the whole data set ($\hat{b}$ = 0.03 m/degree^2) is clearly low when compared to the individual estimates, which mean value looks closer to 0.04 m/degree^2.

The scatter of $\hat{b}$ during the GM is surprising because the number of crossover data in each pseudo-cycle is (on average) 2.7 times larger than the number of data in each ERM cycle. The standard deviation of $\hat{b}$ for the GM should therefore be roughly 1.6 ($\sqrt{2.7}$) time smaller than the standard deviation for the ERM. Quite the contrary, one observes an increased variability during the GM. This certainly indicates that the residual attitude bias has a more complex and variable behavior during the GM than during the ERM.

The low estimate of b deduced from the regression with the whole data set appears to be essentially due to GM data and, in particular, to a few anomalous pseudo-cycles (numbered 45,47,58 and 59, in figure 3) for which the estimated value of b is close to zero or even negative. This is confirmed when performing regression (7) with the GM and ERM data separately. Regression yields $\ddot{b}$ =0.038 for the ERM and $\ddot{b}$ =0.026 for the GM. But when the 4 anomalous pseudo-cycles are eliminated from the GM data set, the estimated value of b becomes 0.039, in excellent agreement with the ERM estimate.

Further examination of the attitude bias and its variability would be useful but is beyond the scope of the present work. At this stage, our findings can be summarized as follows :

1) the range measurements in the GEOSAT JGM3 GDRs clearly contain a residual attitude bias (δATB)

2) this bias is generally well represented by the simple model (5) : $\delta ATB = b\,[\xi^2 - \langle\xi^2\rangle]$

3) estimates of parameter b, deduced from linear regressions, are reasonably stable for the different cycles of the ERM but are surprisingly scattered for the different pseudo-cycles of the GM

4) the regression performed over the whole ERM data set yield $\hat{b}$ =0.038 m/degree^2. The standard deviation of the different estimates obtained for individual ERM cycles is 0.01. Assuming that these individual estimates are independent, the standard deviation of the estimate deduced from the whole ERM (44 cycles) is $0.01/\sqrt{44} = 0.0015$.

5) the above-mentioned estimate of b appears to be valid for most, but not all, GM pseudo-cycles.

We thus recommend to apply the following residual attitude bias correction to all ERM data :

$$\delta ATB = 0.038\,[\xi^2 - 0.45] \qquad (8)$$

For the GM, correction (7) is generally recommended but its effect should be carefully evaluated on a case by case basis.

5. DETERMINATION OF THE SEA STATE BIAS

As described in section 1.2, we will now try to find the SSB model of the generic form (2), with the smallest possible number of adjustable parameters and that yields residuals of regression (3) as little correlated as possible with SWH and U.

Regressions are performed using range data that have been corrected for the residual attitude bias (8). As previously mentioned, the modeled attitude bias is almost entirely decorrelated from SWH and U. Therefore, applying or not this correction has no significant impact on SSB estimation. Conversely, the SSB estimates obtained here are valid whether or not the δATB correction is applied

After δATB correction, the variance of ΔSSH'is 199.61 cm^2, for the whole data set. That is a standard deviation of 14. 1 cm. Just to have an idea of the maximum amount of variance one can hope to explain with SSB models like (2), we performed regression (3) with the full 6–parameter model. Using the so-determined SSB correction, the variance of the crossover differences goes down to 185.10 cm^2 (standard deviation of 13.6 cm). The variance explained is thus 14.51 cm^2, or 3.8 cm rms.

5.1 ONE-PARAMETER MODEL

5.1.1 Parameter estimates

Regression (3) performed with the simple BM1 model (2), yields $\hat{a}_1$ = -0.024. That is a SSB equal to -2.4 % of SWH. This is somewhat larger (i.e. more negative) than the -2 % value obtained for TOPEX (Gaspar et al., 1994) but consistent with the previously published values of the GEOSAT SSB (between -1 and -3.6 % of SWH according to the review of Ray and Koblinsky, 1991). This uncertainty was mostly due to the presence of relatively large orbit errors in the first versions of the GEOSAT GDRs. This error has now been drastically reduced and estimates of a_1 deduced from regressions performed on individual cycles or pseudo-cycles exhibit a relatively low variability (figure 4). This variability is clearly smaller for GM pseudo-cycles than for the ERM cycles, as expected. Also estimates of a_1 separately deduced from the GM and ERM data sets are virtually identical, the difference being below 0.1 % of SWH. So, contrary to what was observed with the residual attitude bias, the behavior of the SSB appears to be very stable throughout the whole GEOSAT mission. This is consistently observed in all analyses performed with the more elaborate models presented in the next sections.

Based on the estimates deduced from individual (pseudo-)cycles, and assuming that these are independent, the uncertainty (σ) on the estimate of a_1 obtained with the whole data set is given by :

$$\frac{1}{\sigma^2} = \frac{44}{\sigma^2_{ERM}} + \frac{24}{\sigma^2_{GM}} \tag{9}$$

where σ^2_{ERM} and σ^2_{GM} are the variances of the individual coefficient estimates computed over the ERM and GM respectively. In this case, the resulting value of σ is 4 10^{-4}.

5.1.2 Variance explained

With the simple BM1 SSB correction, the variance of the crossover differences goes down to 187.35 cm^2. The variance explained by BM1 is thus 12.26 cm2, that is 84 % of the variance explained by the full 6-parameter model. Unfortunately the simple BM1 model still leaves regression residuals that are strongly correlated with both ΔSWH and ΔU, as shown in Figure 5. It is thus useful to investigate more elaborate models even if the expected reduction in the variance of the crossover differences is relatively small. The variance explained by all 2-, 3- and 4-parameter models is presented in table 1. The model results and model ranking is discussed in the following paragraphs.

5.2 TWO-PARAMETER MODELS

Among the 2-parameter models, two solutions are clearly ahead and close to a tie in terms of explained variance. These are the models using SWH^2 or SWH^3 as the second regressor. The situation was the same with TOPEX and POSEIDON data. The SWH^3 solution was finally selected as the model coefficients were better determined (i.e. have a smaller uncertainty). This is also the case with GEOSAT data. The best 2-parameter model BM2(G) (where G stands for GEOSAT) is:

$$SSB_m = SWH\ [-0.035 + 0.00018\ SWH^2] \tag{10}$$

Based on (9), the uncertainties (σ) on the first and second coefficients are $6\ 10^{-4}$ and $6\ 10^{-6}$, respectively.

Relation (10) simply expresses that the relative bias (SSB/SWH) of GEOSAT increases (i.e. becomes less negative) when SWH increases. This was first observed by Witter and Chelton (1991b). TOPEX and POSEIDON SSBs behave the same way (Gaspar et al., 1994 ; Chelton, 1994).

The regression residuals for BM2(G) are shown in figure 6. Like for TOPEX and POSEIDON, it is clear that the SWH^3 term added to the BM1 model significantly reduces the SWH-related variations in the residuals. Mean residuals are very small (below 5 mm in absolute value) except for $\Delta SWH < -3$ m. Crossover data with such very negative values of ΔSWH are few (less than 2.5 % of the whole data set). The mean residuals sorted according to ΔU are also small but exhibit a very clear trend as a function of ΔU. This leads us to go one step further and consider 3-parameter models.

5.3 THREE-PARAMETER MODELS

In terms of explained variance (table 1), one model is very clearly ahead. This best 3-parameter model, BM3(G) reads

$$SSB_m = SWH\ [a_1 + a_3\ U + a_6\ SWH\ U] \qquad (11)$$

The coefficient estimates with their uncertainties ($\pm\ \sigma$) are :

$\ddot{a}_1 = -0.0250 \pm 6\ 10^{-4}$; $\ddot{a}_3 = -0.00145 \pm 4\ 10^{-5}$; $\ddot{a}_6 = 0.00020 \pm 5\ 10^{-6}$

The regression residuals are plotted in figure 7. They are very small both when binned as a function of ΔU and as a function of ΔSWH. Mean values are generally below 5 mm and always below the centimeter level. The explained variance is 14.16 cm2, that is over 97 % of the variance explained by the full 6-parameter model. It thus appears that we have now identified a suitable SSB model for the GEOSAT data. This is the model we recommend for use. The corresponding relative bias is plotted in figure 8.

A bit surprisingly, the formulation of BM3(G) is (slightly) different from the formulation of the best 3-parameter model for TOPEX and POSEIDON (BM3(T) and BM3(P)) identified by Gaspar et al. (1994) and Chelton (1994). A small difference between the processing of the TOPEX-POSEIDON and GEOSAT data is worth mentioning. For GEOSAT data, the wind speed is computed with the Freilich and Challenor algorithm (1994). For TOPEX-POSEIDON, it is computed with the Modified Chelton-Wentz (MCW) algorithm (Witter and Chelton, 1991a). The corresponding difference in wind speed estimation is relatively small but we nevertheless checked that it does not significantly affect our results. To this aim, we performed series of regressions with all possible 3-parameter models using the MCW algorithm instead of Freilich and Challenor (1994). The results are very close to those previously obtained :

- BM3(G), with an explained variance of 14.19 cm2, clearly remains the best 3-parameter model.
- The new estimates of the BM3(G) parameters are well within the error bars of the previous estimates obtained with the Freilich and Challenor (1994) algorithm.

This clearly indicates that the skill of BM3(G) is, by no means, related to the choice of the wind speed algorithm. The difference in the formulation of BM3(G) and BM3(T/P) thus remains intriguing and worth a small discussion.

5.4 DISCUSSION

The difference between BM3(G) and BM3(T/P) is in the last term only : SWH^2U for GEOSAT, $SWHU^2$ for TOPEX and POSEIDON. Interestingly, (11) was the second best 3-parameter model for TOPEX and POSEIDON (Gaspar et al., 1994), while the BM3(T) formulation comes second amongst the GEOSAT 3-parameter models. These are thus relatively good models for the 3 altimeters, even if the SSB behavior that they simulate is a bit different :

1) The relative bias of the well-known BM3 (T) model, first proposed by Hevizi et al. (1993), is a quadratic function of U only : the simulated relative bias decreases (i.e. becomes more negative) with U for wind speeds up to about 10 m/s and then increases at higher wind speeds.

2) The relative bias of the BM3(G) model is a function of both U and SWH. The coefficient a_6 being positive, the relative bias always increases with SWH. This mimics the behavior simulated by BM2. On the other hand, the relative bias varies with wind speed at a rate

equal to $a_3 + a_6$ SWH. This rate of change is negative for SWH < 7.25 m, a criterion that is nearly always verified (over 98.5 % of the SWH measurements in our data set are below 7.25 m). This decrease of the relative bias with increasing wind speed is also simulated by BM3(T), but only at wind speeds below 10 m/s. At higher wind speeds BM3(T) simulates an increase of the relative bias. With BM3(G), this can only occur at exceptionally high wave heights (that are generally associated with high wind speeds !).

To summarize, one can identify 3 characteristic behaviors of the relative bias simulated by 3-parameter models of the BM3(T) and/or BM3(G) type :
[1] an increase of the relative bias with SWH
[2] a decrease of the relative bias with U at moderate wind speeds (say below 10 m/s)
[3] an increase of the relative bias with U at high wind speeds

BM3(G) simulates [1] and [2] while BM3(T) simulates [2] and [3]. Behavior [1] is known to be present in TOPEX and POSEIDON data (Gaspar et al., 1994 ; Chelton, 1994). But a 3-parameter model simply cannot simulate [1], [2] and [3], all together. This is why a 4-parameter model, BM4(T), was developed to simulate the TOPEX SSB.

For GEOSAT, we have just showed that a 3-parameter model, not simulating [3], is sufficient. Does this mean that the GEOSAT relative bias does not increase with U at high wind speeds ? This can be checked using a non-parametric SSB estimation technique (Rodriguez and Martin, 1994 ; see this paper for a detailed description of the method). The estimation principle is simple; the SSB is written under the form :

$$SSB_m = SWH\ f(U) \tag{12}$$

where the function f(U), the relative bias, is not analytically specified but evaluated at discrete intervals, i.e. for a set of regularly sampled values of U : U_i, i= 1,n. The unknown of the estimation process are thus the n discrete values $f(U_i)$. The main advantage of this method is that no a priori assumption is made on the shape of f. Rodriguez and Martin (1994) first used this technique to analyze the behavior of the TOPEX SSB. Their results confirmed that the TOPEX relative bias closely followed a quadratic law in U, as simulated by the parametric model BM3(T). We have performed the same type of analysis with the whole GEOSAT data set. Values of f(U) are estimated at 2 m/s intervals in the range 1.5 m/s<U<19.5 m/s. The result is presented in figure 9. The figure clearly shows that the relative bias indeed decreases for wind speeds up to 9.5 m/s and then increases, but only slowly, at higher wind speeds. The rate of decrease is about 3 times smaller than the rate of increase. This asymmetric behavior is not well represented by a quadratic law. This is probably why a model like BM3(T) does not perform very well with GEOSAT data. Figure 9 also reveals that BM3(G) is not totally adequate as it cannot simulate the (weak) increase of the relative bias at high wind speeds. Interestingly, table 1 shows that the best 4-parameter model, BM4(G) contains the 3 terms of BM3(G) plus a SWH U^2 term that actually yields this increase of the relative bias at high wind speeds. Adding this term does not appear to be justified here as it provides no clear improvement of the regression residuals. In addition, the differences between SSBs estimated with BM3(G) or with BM4(G) are generally very small. For the whole data set, the mean difference is 6 mm with a standard deviation of only 4 mm. We are thus generally below the centimeter level.

6. SUMMARY AND CONCLUSION

The new JGM3 GDRs (Cheney, 1996) have been used to analyze and estimate the GEOSAT SSB. The analysis is based on a crossover data set covering over 3.5 years, including the whole GM and most of the ERM. The SSB determination method is the one previously used by Gaspar et al. (1994) to estimate the TOPEX and POSEIDON SSB. The main results are:

1 . The GEOSAT SSB is well represented by the following 3-parameter linear model:

$$SSB_m = SWH\,[-0.025 - 0.00145\,U + 0.00020\,SWH\,U]$$

2 . GEOSAT data contain a residual attitude bias (δATB) that is generally well modeled by:

$$\delta ATB = 0.038\,[\xi^2 - 0.45]$$

This estimate is valid for all ERM data. It is generally valid for the GM, with the exception of a few pseudo-cycles. The effect of this correction should thus be carefully evaluated when using it with GM data.

3 . The residual attitude bias correction is not significantly correlated with the SSB correction. Therefore the proposed SSB correction can always be used, whether or not the δATB correction is applied.

The above mentioned SSB and residual attitude bias corrections are now featured in the GEOSAT JGM3 GDRs.

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SWH	**SWH^2**	**SWH^3**	**SWH U**	**SWH U^2**	**SWH^{2}U**	**Variance explained (cm2)**
			2-parameter models			
X				X		12.27
			X			12.40
X					X	12.56
X	X					13.26
X		X				13.30
			3-parameter models			
X	X	X				13.30
X	X				X	13.35
X				X	X	13.37
X		X			X	13.38
….X	X			X		13.39
X		X		X		13.41
X	X		X			13.65
X		X	X			13.66
X			X	X		13.69
X			X		X	14.16
			4-parameter models			
X	X	X			X	13.39
X	X	X		X		13.42
X	X		X		X	13.42
X		X		X	X	13.43
X	X	X	X			13.67
X	X		X		X	14.21
X		X	X		X	14.24
X		X	X	X		14.43
X	X		X	X		14.44
X			X	X	X	14.50

Table 1 : Variance of the GEOSAT crossover differences explained by the 2-,3- and 4-parameter SSB models. Crosses indicate the terms of the full model (2) that have been retained.

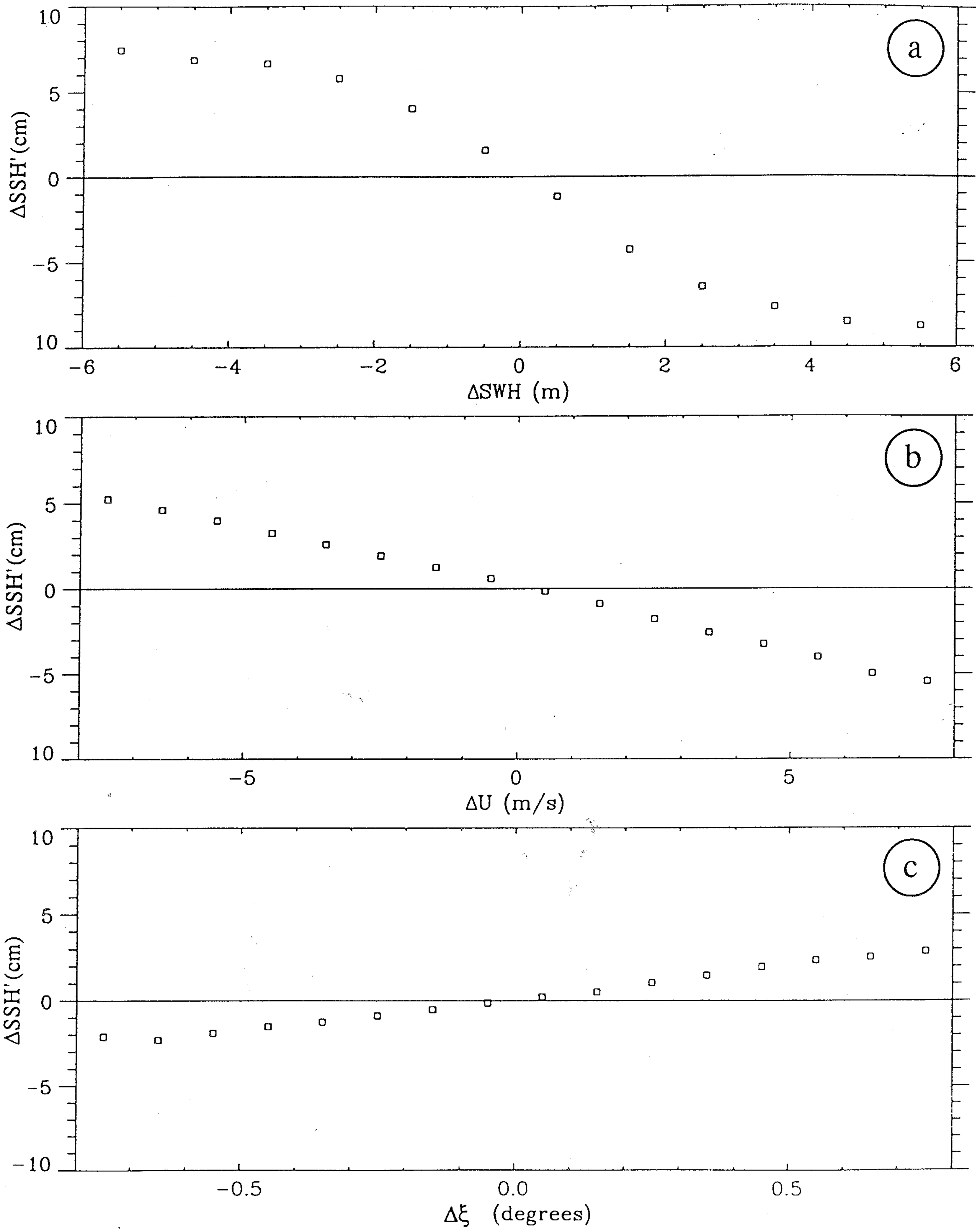

Figure 1: GEOSAT mean crossover differences before SSB correction as a function of (a) Δ SWH, (b) Δ U and (c) $\Delta\xi$. The squares show averages computed on bins of width 1m for Δ SWH, 1m/s for Δ U and 0.1° for $\Delta\xi$.

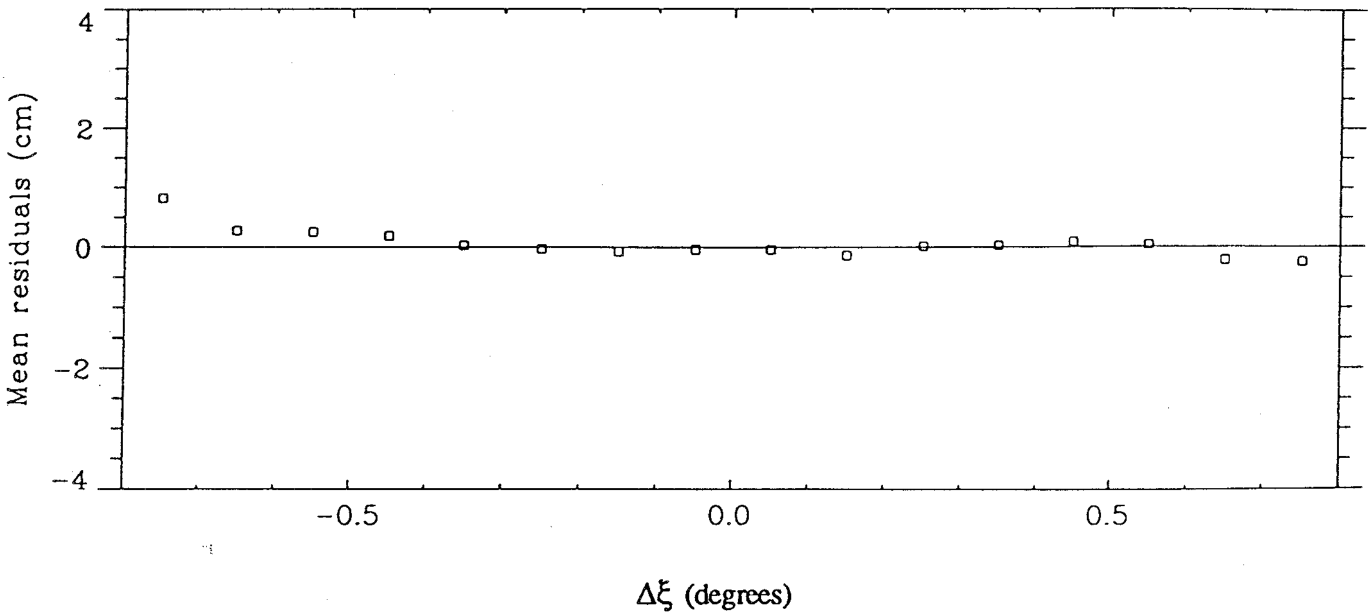

Figure 2: Mean residuals of regression (6) as a function of $\Delta\xi$. The squares show averages computed on $\Delta\xi$ bins of 0.1°.

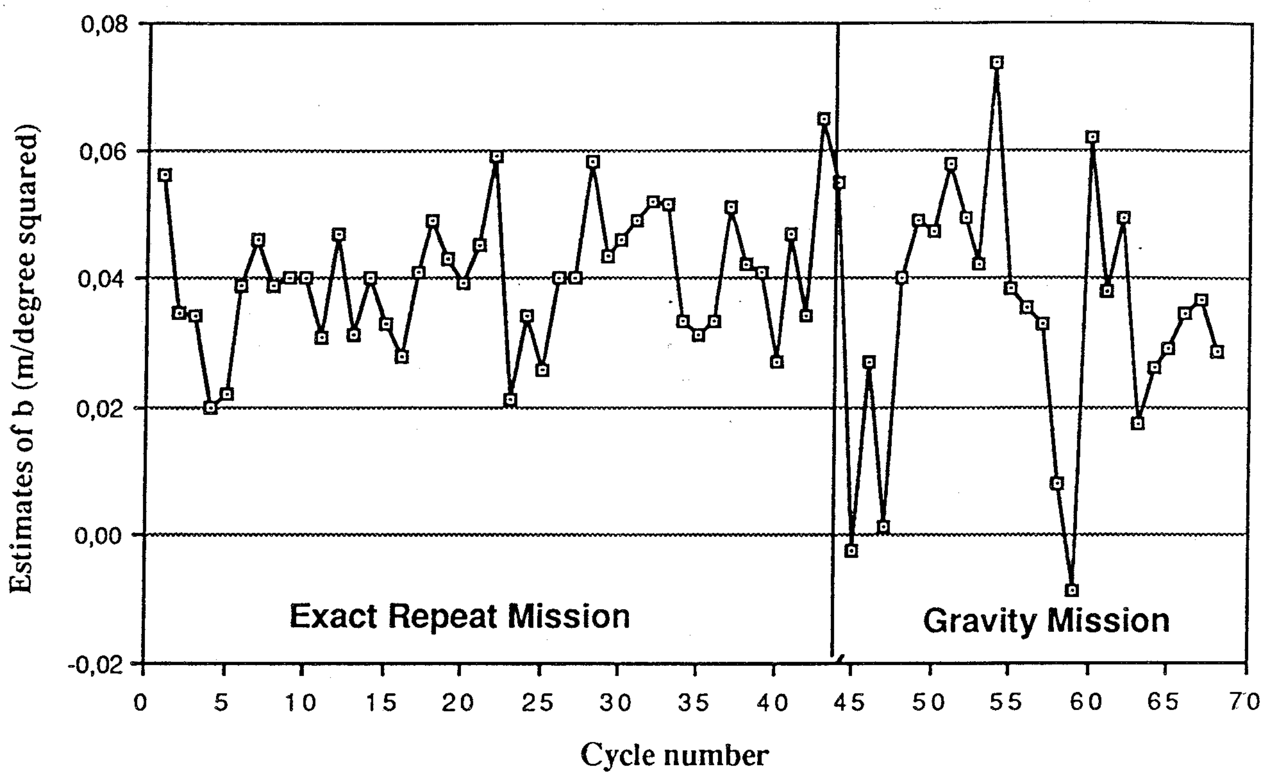

Figure 3 : Estimates of parameter b deduced from regression (7) performed over individual (pseudo-)cycles. ERM cycles are number 1 to 44. GM pseudo-cycles are number 45 to 68.

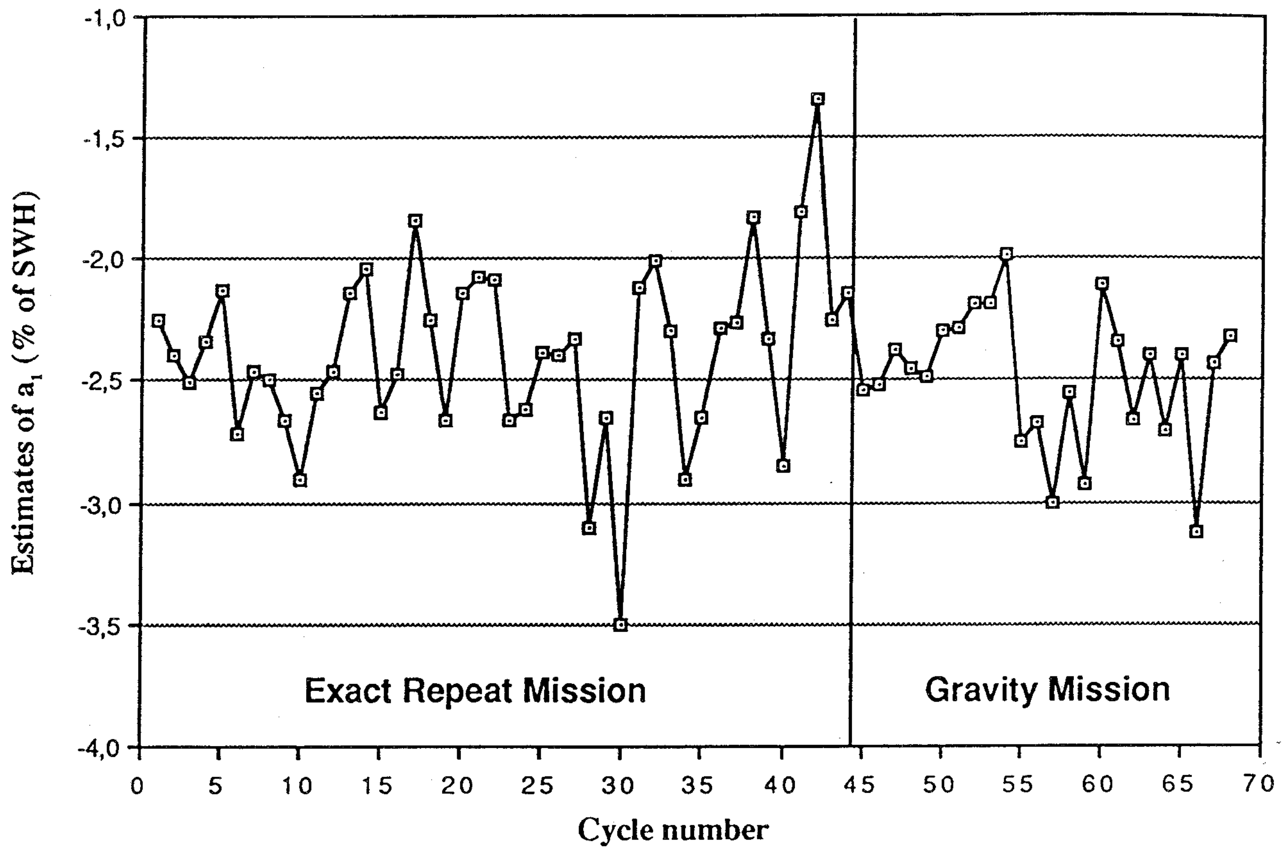

Figure 4 : Estimates of a_1 (in % of SWH) deduced from regressions performed with the BM1 model over individual (pseudo-)cycles.

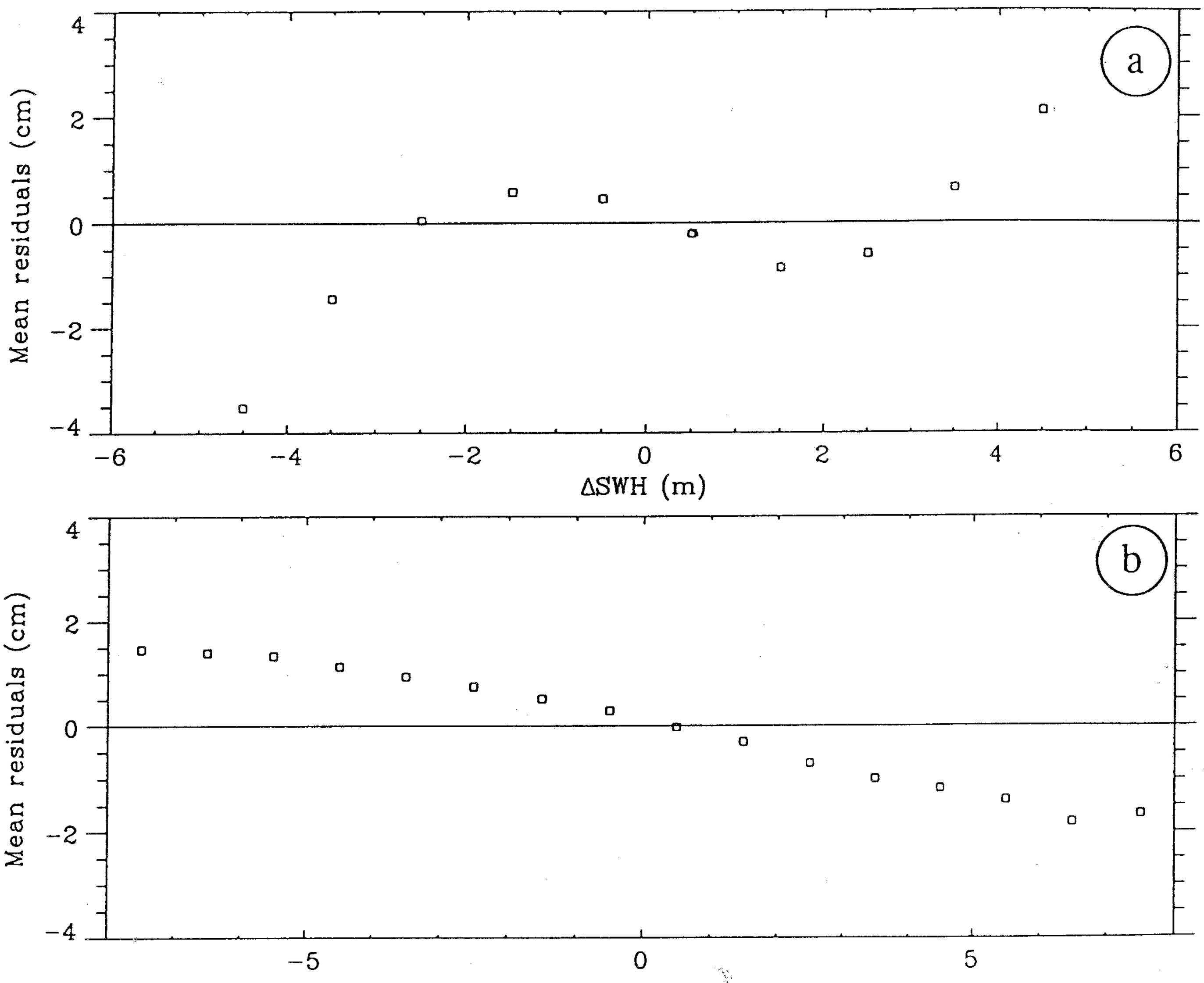

Figure 5: Mean regression residuals for BM1 as a function of (a) Δ SWH and (b) Δ U. As in figure 1, means are computed on bins of width 1 m for Δ SWH and 1m/s for Δ U.

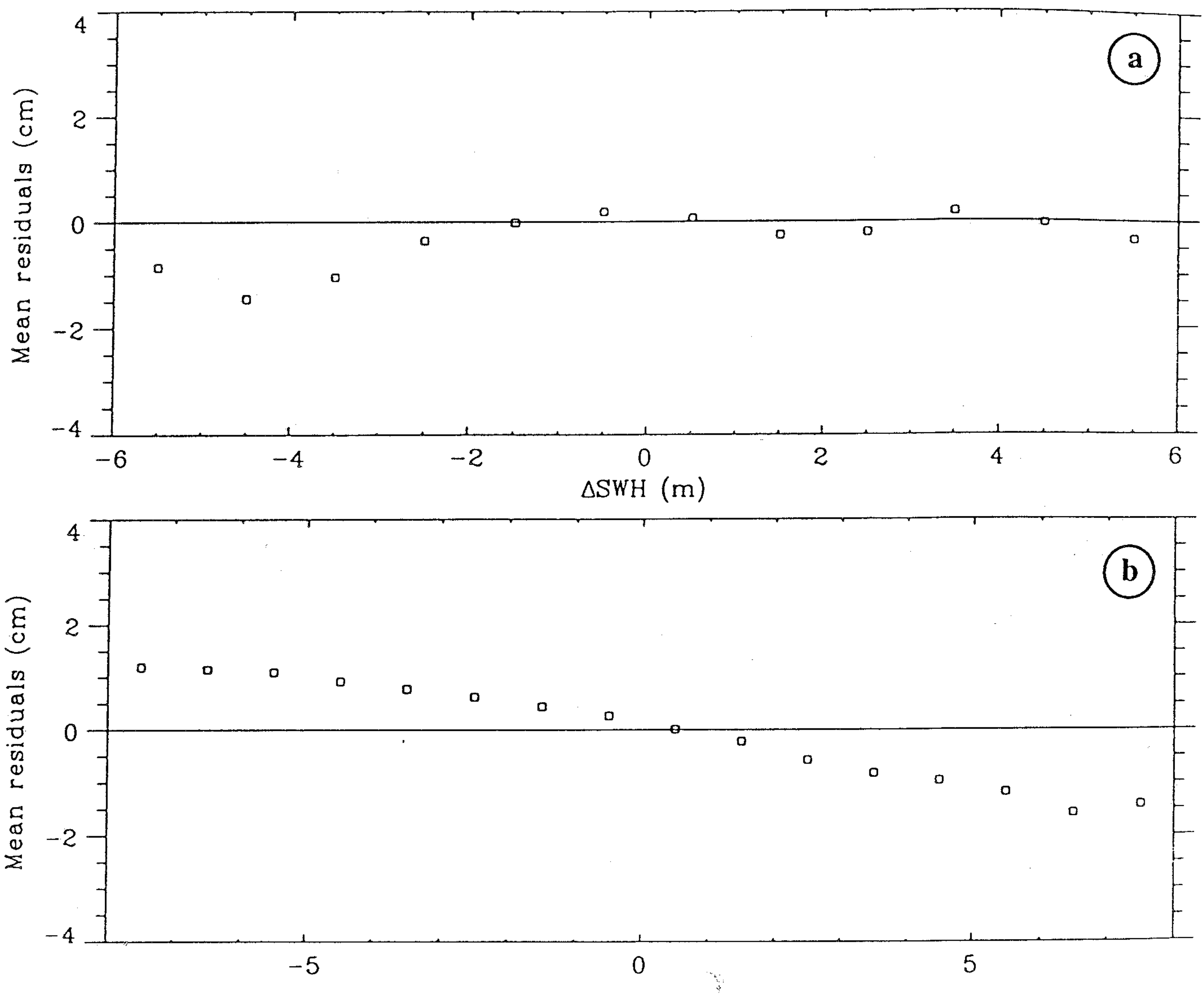

Figure 6: As in figure 5 but for BM2(G) (equation (10)).

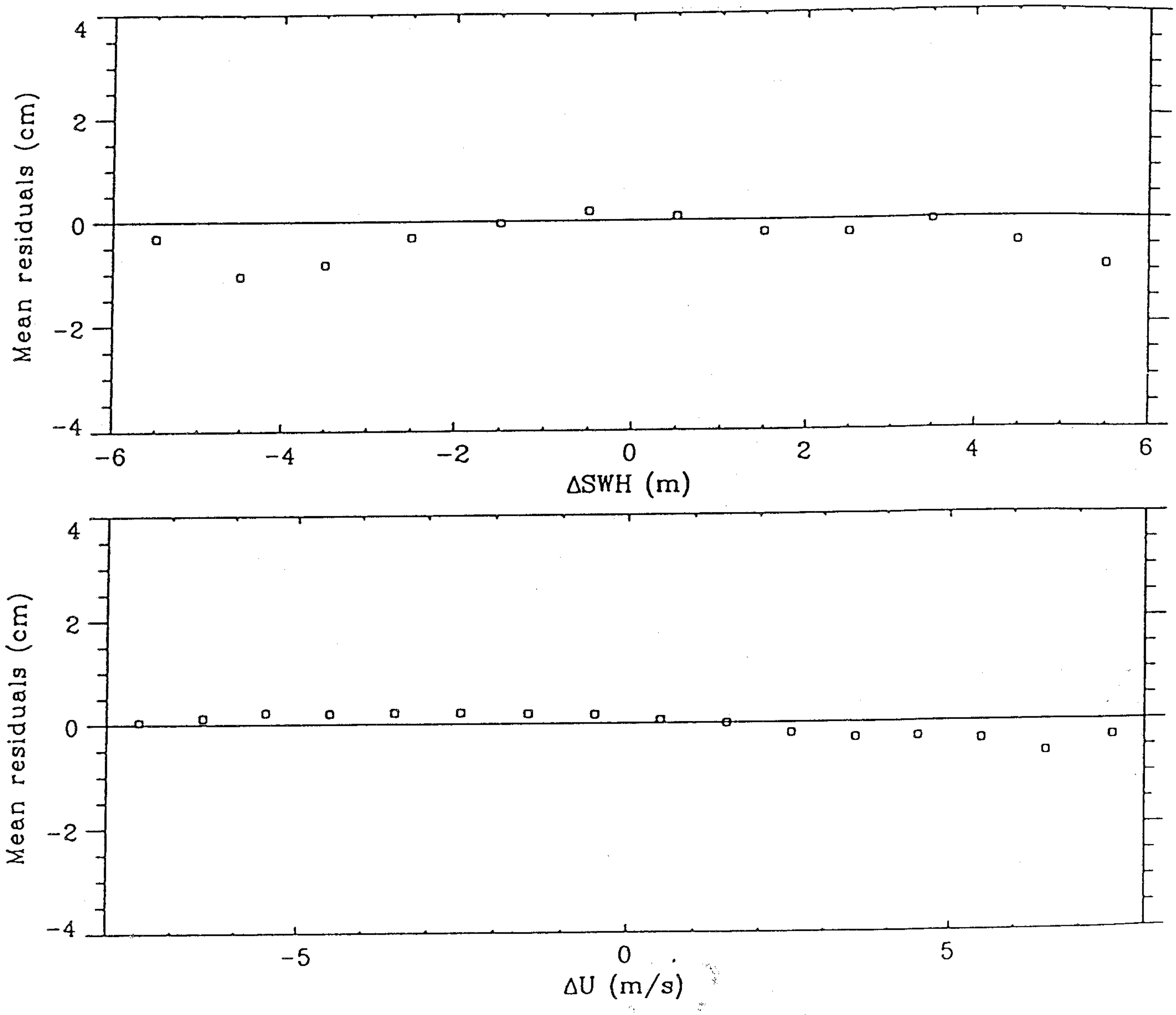

Figure 7: As in figure 5, but for BM3(G) (equation (11)).

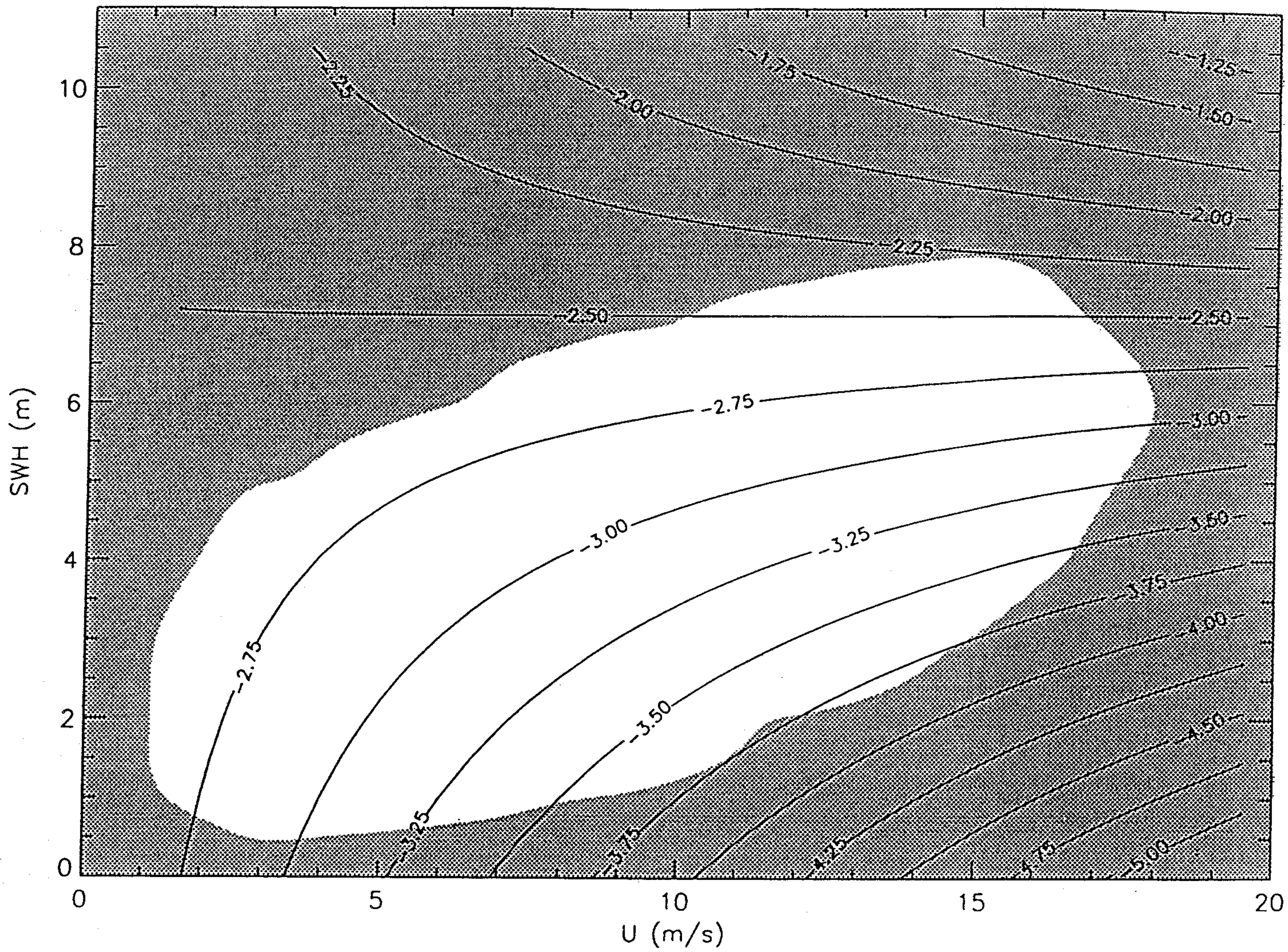

Figure 8: Relative bias (% SWH) for the BM3(G) model.
The shading outlines the region with little or no data coverage; 95% of the (SWH, U) measurements are in the not-shared area.

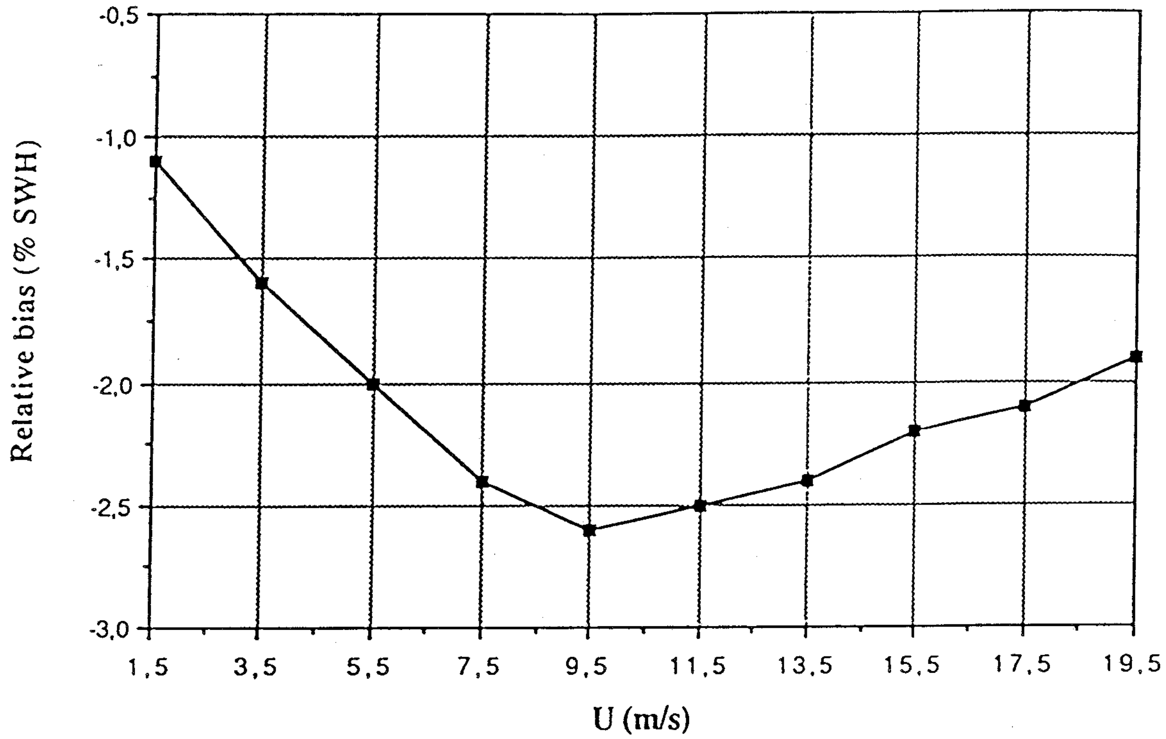

Figure 9: Relative bias as a function of wind speed determined by the non-parametric method.